ON THE ASSOCIATION OF MAGNETIC CLOUDS AND GEOMAGNETIC STORMS

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ABSTRACT

Evidence is given linking magnetic clouds reported at Earth and "gradual commencement" principal magnetic storms. About half of 19 magnetic clouds could be associated with geomagnetic storms beginning within 1 hr of cloud commencement at Earth, while none of 19 controls (no magnetic clouds reported at Earth) could be associated with storms. The association is significant at better than 99% level of confidence. Superposed epoch analysis of the equatorial Dst geomagnetic index for time intervals associated with the 19 magnetic clouds, centered on start time of clouds at Earth, reveals that <Dst> steadily decreased, by a factor of about 5, between cloud onset and 13 hr following cloud onset, when it began a slow recovery to pre-cloud values. Superposed epoch analysis for time intervals associated with the 19 controls, centered on the start time of the control periods, shows <Dst> to vary only insignificantly as compared to pre-cloud values. The decrease (and subsequent increase) in <Dst> for the timespans associated with the clouds is shown to be directly related to the behavior of Bz, the Z-component of the interplanetary magnetic field; i.e., from superposed epoch analysis, the decrease in <Dst> is seen to simultaneously occur with a sustained southward <Bz>, with the recovery of <Dst> beginning with the occurrence of northward <Bz>.

INTRODUCTION

The existence of interplanetary magnetic clouds has been clearly attested by Burlaga _et al_. [1981] and Burlaga and Behannon [1982], and the statistical characteristics of clouds have been described by Klein and Burlaga [1982; hereafter referred to as KB]. KB grouped 45 magnetic clouds into three, approximately equally populated classes: group A clouds following shocks, group B clouds preceding interaction (co-rotating) regions, and group C clouds associated with cold magnetic enhancements. KB classified the magnetic clouds in this way, not that each class of clouds is inherently different from each other (their field and plasma parameters, in fact, were quite similar in value), but that the three types of clouds were identified according to the environment in which they were found. KB believed that the three classes of clouds might be different manifestations of a single phenomenon, in particular, earthward-directed coronal mass ejections (CMEs). All clouds were identified near Earth from observations made with the IMP series of spacecraft.

Support for this hypothesis (i.e., magnetic clouds are associated with CMEs) has grown. For example, Burlaga _et al_. [1982] found that a plane-of-sky magnetic cloud was associated with a plane-of-sky CME, based on Helios 1 and Solwind data. Also, Wilson and Hildner [1984] showed that group A magnetic clouds often were associated with flare-related type II meter-wave radio bursts near central meridian, based on a statistical study of magnetic clouds, controls (no magnetic clouds), and proxy CME-related solar events. More recently, Wilson and Hildner [1986] found groups B and C magnetic clouds to be statistically associated (at > 99% level of confidence) with disappearing filaments near central meridian.

CMEs often have been associated with two forms of solar activity: flare-related type II radio bursts and disappearing filaments (erupting prominences) [e.g., Munro et al., 1979; Rust and Hildner et al., 1980; Wagner, 1984; Cane and Stone, 1984; Sheeley et al., 1985; Cane, 1985]. These same two forms of solar activity, when they occur near central meridian, also have been associated with geomagnetic storms [e.g., Hundhausen, 1979; Joselyn and McIntosh, 1981; McNamara and Wright, 1982; Wright and McNamara, 1983; Rust, 1983; Sastri, Ramesh, and Rao, 1985]. Therefore, if magnetic clouds near Earth, indeed, are manifestations of CMEs directed at Earth, then they too may be associated with geomagnetic storms.

It is generally accepted that sudden commencement geomagnetic storms are associated with enhancements of solar wind dynamic pressure (i.e., shocks) [Burton, McPherron, and Russell, 1975; Cane, 1985]. Likewise, the Z-component (Bz) of the interplanetary magnetic field (IMF) has been associated with geomagnetic activity [e.g., Rostoker and Fälthammar, 1967; Russell, McPherron, and Burton, 1974]. Disturbances in the Earth's magnetosphere often are monitored using the Dst geomagnetic index. In this paper, the statistical association between magnetic clouds near Earth and geomagnetic storms is investigated, using both an event (cloud) group and a control (no cloud) group. Also, based on superposed epoch anaylsis, the time-dependent behavior of <Dst>, the mean equatorial Dst geomagnetic index, and of <Bz>, the mean Bz of the IMF, for 19 magnetic clouds and 19 controls is determined. Lastly, a comparison is made of clouds with known geomagnetic storm associations against those without known storm associations.

DISCUSSION

Approach

Based on KB's [1982] listing of cloud occurrences between May 1973 and April 1978, a comparison is made between the start time of cloud occurrence at Earth and principal magnetic storm commencement as listed in the Solar Geophysical Data, denoting "yes" associations as those when a principal magnetic storm commenced within 1 hr of the start of a cloud at Earth. The analysis is performed by cloud group and for the combined groups B & C clouds and all clouds. For comparison, control periods (no magnetic clouds reported at Earth) are also employed.

In the contingency tables of observed distributions, clouds are denoted by the letter "E," signifying "event," and controls by the letter "C." Statistical testing, based on the probability P that there is no preferential association between clouds and geomagnetic storms, is used to determine the significance of the observed distributions.

Next, the type of geomagnetic storm that possibly may be associated with magnetic clouds is investigated; i.e., are magnetic clouds better associated with gradual commencements or sudden commencements? This is accomplished by means of statistical testing, as before, based on the probability P that there is no preferential association in the distributions.

Lastly, superposed epoch analyses of Dst and Bz are performed, for the interval 24 hr either side of cloud and control onsets at Earth and based on hourly values published, respectively, in the SGD and in King [1977, 1979]. <Dst> and <Bz> are computed for the 19 clouds and 19 controls and their time-dependent behavior is compared. A similar analysis is performed in which the behavior of <Dst> and <Bz> for clouds with known geomagnetic storms is contrasted against those without known geomagnetic storms.

In all of the analyses, the control groups are the same and were determined by off-setting later in time (typically 7 to 9 days) from the start of the clouds as reported by KB [1982]. Since magnetic clouds average about 24 hr in duration, all control periods are 24 hr in duration, as well. For convenience, all control periods begin at 0000 UT. A control period is defined as a period of time in which no magnetic cloud was reported by KB, yet the solar wind data are of sufficient quality that had a magnetic cloud been present it should have been contained in their original list. Also, the control period should be sufficiently later in time so that the longitude of activity is no longer near central meridian. Because of these constraints, the control periods spanned typically 7 to 9 days later. [Additional comments regarding controls are contained in Wilson and Hildner, 1986.]

Magnetic Cloud-Geomagnetic Storm Associations

In Table 1 the observed distribution is shown of "yes" and "no" associations for the event (cloud) group and the control (no cloud) group for the different classes of magnetic clouds and selected groupings of clouds, based on the sorting criterion of geomagnetic storms commencing within 1 hr of the start of a cloud (or control) at Earth. For group A clouds (those following shocks), 2 of 4 clouds meet this criterion; the 2 clouds which did not meet the criterion had storms already in progress, apparently due to the shocks which preceded the clouds -- one 14 hr prior to cloud passage at Earth and the other 9 hr prior to cloud passage. For group B clouds (those preceding interaction or co-rotating regions), 3 of 7 have associated geomagnetic storms, and for group C clouds (those associated with cold magnetic enhancements), 5 of 8 have associations. For the combined groups B & C, 8 of 15 have associations, and for the overall combined group (all magnetic clouds ignoring cloud class), 10 of 19 magnetic clouds have associated geomagnetic storms. In all categories, none of the controls has any association with geomagnetic storms.

The probability P that <u>no</u> preferential association exists in the observed distribution, likewise, is given in Table 1 for the various classes of magnetic clouds, computed using the hypergeometric formula [Langley, 1971; Everitt, 1977]. The only groupings which exhibit a statistically significant ($P \lesssim 0.05$) association are groups C, B &C, and the overall combined group (all clouds). In fact, the associations for groups B &C and ALL are significant at > 99% level of confidence ($P < 0.01$). Thus, the observed distribution of near simultaneous occurrences (commencements within 1 hr of each other) of magnetic clouds near

Earth and geomagnetic storms strongly suggests that the association is not random, but rather preferential, with geomagnetic storms often occurring when magnetic clouds (associated with CMEs) are present near Earth.

Gradual Commencement Versus Sudden Commencement

In Table 2 the observed distribution is shown of "yes" and "no" associations by type of geomagnetic storm for each class of cloud and for selected groupings of clouds, again based on event and control groups. For group A clouds, none of the magnetic clouds can be associated with gradual commencement storms. Instead, they appear to be better associated with sudden commencement storms; 2 of 4 clouds have associated sudden commencements. (Actually, all 4 clouds are associated with sudden commencements; only 2 of the 4 met the criterion of having a storm commence within 1 hr of cloud onset at Earth.) This may be an expected result, since Cane [1985] has shown that interplanetary shocks (i.e., sudden commencements) often are associated with type II radio emission on the Sun, and Wilson and Hildner [1984] have shown that group A magnetic clouds (those associated with shocks), likewise, often are associated with type II radio emission.

For the other groupings of clouds, 3 of 7 group B clouds and 5 of 8 group C clouds have associations with gradual commencements. (None of these two classes of clouds had associations with sudden commencement storms.) Thus, about half (8 of 15) of the combined groups B and C clouds appear to be closely associated with gradual commencement storms. Ignoring magnetic cloud group classification, 8 of 19 appear to be associated with gradual commencements, while 2 (both group

A clouds following shocks) have sudden commencements; as stated earlier, no controls have associations with either form of geomagnetic activity.

The probability P that no preferential association exists in the observed distribution (for each class of magnetic clouds) is also given in Table 2. As in Table 1, the only groupings which exhibit a statistically significant result ($P \lesssim 0.05$) are groups C, B & C, and the overall combined (all classes) group, with associations for groups B & C and the overall combined group being significant at > 99% level of confidence. Thus, the observed distributions strongly suggest a preferential association between magnetic clouds near Earth and gradual commencement geomagnetic storms.

Superposed Epoch Analyses

In Figure 1a, the result of a superposed epoch analysis of the time intervals for the 19 magnetic clouds, ignoring group designation, is depicted. Each of the 19 magnetic clouds was aligned according to time of onset of cloud passage at Earth, and the Dst geomagnetic index values were combined and averaged to yield a mean <Dst> value. The time interval of 24 hr prior to cloud passage is designated "pre-cloud," while the 24-hr interval following cloud onset is denoted "cloud." Mean value ($\bar{x}$), standard deviation (s), and number of individual data points (n) are identified for the pre-cloud timespan. [It is noted that the Dst index is a measure of the total kinetic energy of particles in the symmetric part of the ring current belt and is useful in studies of geomagnetic storms; Dessler and Parker, 1959; Burton, McPherron, and Russell, 1975; and Akasofu et al., 1985.]

<Dst> is observed to vary insignificantly during the pre-cloud interval. Commensurate with cloud onset, <Dst> began a steady 13-hr decrease to a value about 5 times more negative than the mean value (-7.4) for the pre-cloud interval. Following this, <Dst> began a slow increase to pre-cloud values. This signature of sudden commencement, main phase, and recovery is typical for distrubances monitored using the Dst index.

In Figure 1b, a similar plot of the time intervals for the 19 controls is depicted, where each control is aligned according to control start. Where before a sudden decrease in <Dst> to large negative value is observed for the cloud interval relative to the pre-cloud interval, no such behavior is noted for the controls. Instead a slowly varying signal is observed, whose mean value differs insignificantly from that of the pre-cloud <Dst> mean value. (The 95% confidence interval for the pre-cloud <Dst> mean value is -7.4 ± 1.9 and the 95% confidence interval for the control <Dst> mean value is -9.1 ± 1.1. Thus, the means of the two distributions are insignificantly different at the 95% level of confidence; in fact, they are even insignificant at the 90% level of confidence.)

In Figure 2, a superposed epoch analysis of the time intervals for the 19 clouds is shown in terms of <Bz>, the mean Z-component of the interplanetary magnetic field. Past research has revealed <Bz> to be generally associated with geomagnetic activity [e.g., Burton, McPherron, and Russell, 1975 and references contained therein]. For example, Rostoker and Fälthammar [1967] found that the main phase of a geomagnetic storm was associated with a sustained southward Bz, and they noted that the recovery phase was associated with a decrease or switching off of the southward Bz. Also, Russell, McPherron, and Burton [1974] found that the southward Bz had to exceed an apparent threshold level, which possibly was Dst-dependent, in order to trigger the main phase of a storm. In Figure 2, <Bz> is observed to vary insignificantly during the pre-cloud interval. (The 95% confidence interval for the <Bz> mean value during the pre-cloud interval is about 0.2 $\pm$ 0.3.) Near the time of cloud onset at Earth (when <Dst> was beginning to decrease), <Bz> is observed to decrease to a maximum southward value within a few hours and to sustain a southward value for several additional hours. <Bz> becomes northward at about 16 hr following cloud onset, and it remains so at least through 24 hr after cloud onset. The northward <Bz> appears to be associated with the recovery phase of <Dst>.

Cloud-Storm Association Differences

It is a curiosity that all magnetic clouds do not appear to have a geomagnetic storm association. Using the criterion of storm commencement within 1 hr of cloud onset at Earth showed that 10 of the 19 magnetic clouds had probable associations with geomagnetic storms. Relaxing this stringent criterion yields an improved association; e.g., a window of $\pm$ 3 hr suggests probable associations for 12 of 19 clouds, and a window of $\pm$ 6 hr increases the number of "yes" associations to 15 of 19. For 5 of the 9 clouds which did not meet the original criterion, a geomagnetic storm was already in progress; thus, 15 of 19 clouds were associated with timespans when geomagnetic activity was enhanced. (In contrast, recall that no-cloud control periods cannot be associated with even a single geomagnetic storm.) For those clouds which had storms already in progress at cloud onset at Earth, the time difference between storm commencement and cloud onset varied between 2 and 14 hr prior to cloud onset.

Figures 3a and 3b depict superposed epoch analyses for <Dst> and <Bz>, respectively, for those with probable cloud-storm associations (10 examples which met the most stringent criterion, denoted ●) and for those without cloud-storm associations (9 examples, denoted ○). In both cases, <Dst> and <Bz> behave similarly. <Dst> and <Bz> are observed to vary insignificantly during the pre-cloud timespan, then to decrease in value near cloud onset at Earth. A main phase and a recovery phase are indicated. The major differences between the two groups are that pre-cloud values of <Dst> for clouds with storms are slightly more positive than for clouds without storms, and that the depth of decrease is slightly greater for clouds with storms. During the cloud interval, <Bz> values for clouds without storms are of slightly more positive value than for clouds with storms. Also, the recovery phase begins sooner for clouds without storms.

In terms of cloud velocity and duration differences, there is essentially no difference between the two groups. Those with associations had an average speed at cloud onset of about 454 km s^{-1}; those without associations about 426 km s^{-1}. Durations averaged 23.8 and 23.9 hr for the two groups, respectively. KB [1982] showed examples of clouds whose magnetic field rotated counterclockwise and clockwise; so, it is not intuitively obvious why some clouds have storm associations and some do not, even though <Dst> and <Bz>

values between the two groups behave similarly and are of about equal magnitude.

CONCLUSIONS

In this paper evidence has been presented that strongly suggests a preferential association between earthward-directed magnetic clouds, manifestations of earthward-directed coronal mass ejections, and geomagnetic storms. The emerging picture is that a magnetic cloud may in some way directly interact with the Earth's magnetosphere as it passes Earth, thereby triggering a geomagnetic storm, and continues into the outer solar system. While group A magnetic clouds following shocks are better associated with sudden commencement geomagnetic storms, the other two classes of magnetic clouds (group B clouds preceding interaction regions and group C clouds associated with cold magnetic enhancements) and clouds in general (all clouds, ignoring cloud classification) appear to better relate to gradual commencement geomagnetic storms, at > 99% level of confidence. The analysis has revealed that about half of the magnetic clouds (10 of 19) and none of the 19 no-cloud controls could be associated with geomagnetic storms. While a 1-to-1 association was not found between magnetic clouds and geomagnetic storms, 15 of 19 clouds could be associated with enhanced periods of geomagnetic activity. Some clouds (about one-fifth) apparently do not trigger storms. Superposed epoch analysis of the 19 clouds and 19 no-cloud controls has revealed that <Dst> for clouds decreased by a factor of about 5 relative to pre-cloud values, while <Dst> for controls varied only insignificantly. The decrease in <Dst> began precisely at the start of cloud passage at Earth and the decrease continued for about 13 hr following cloud start, with a slow recovery to pre-cloud values following. A similar behavior is noted to have occurred for <Bz>. A sustained southward <Bz> occurred near cloud onset at Earth, and when <Bz> became northward, recovery of <Dst> was underway. Both clouds with storm associations and clouds without storm associations exhibit similar behavior in <Dst> and <Bz>, although the <Bz> value for clouds without associated storms is about half that determined for clouds with associated storms and the duration of the southward <Bz> is slightly less. Perhaps, this is suggestive that a threshold level, indeed, exists for triggering geomagnetic storms.

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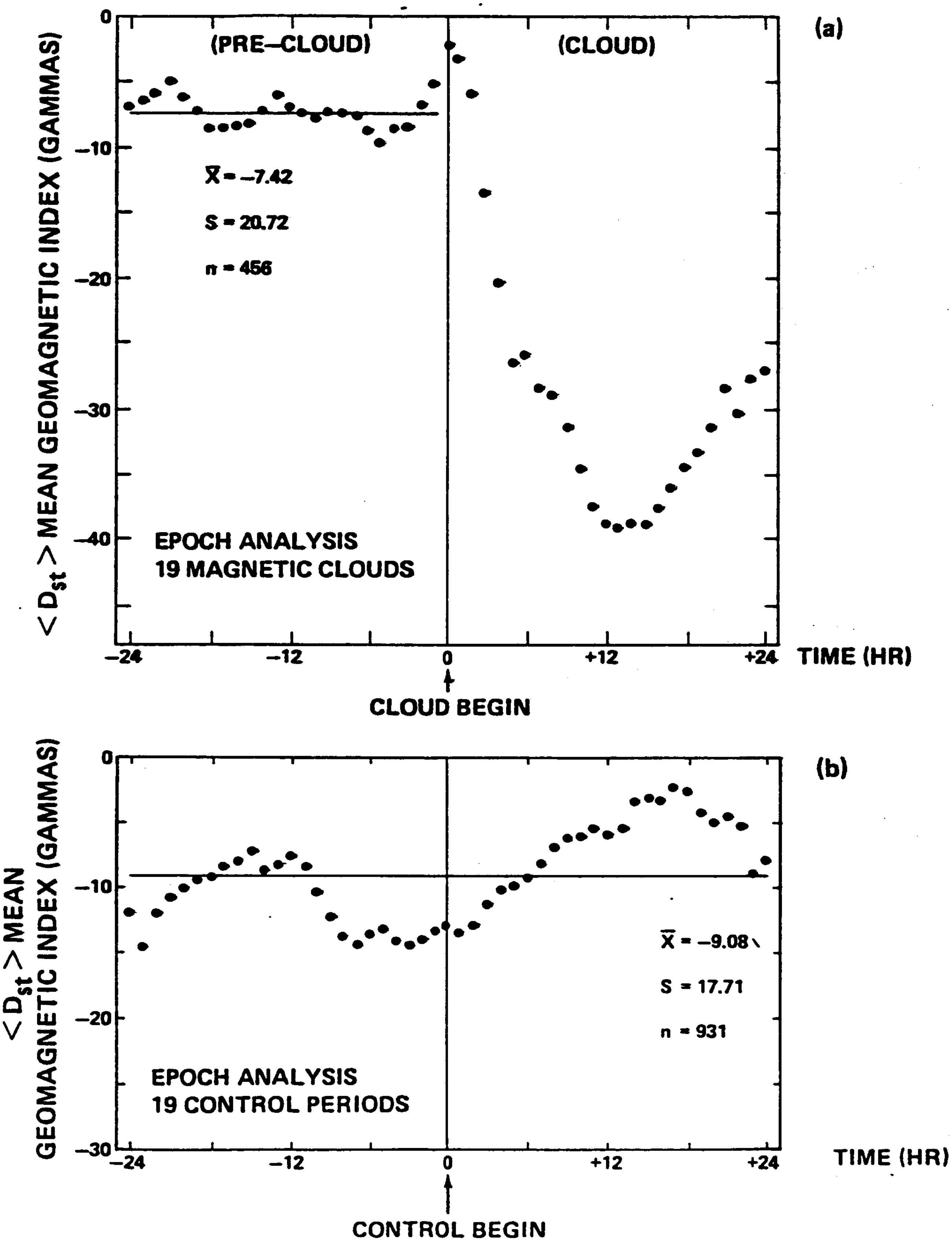
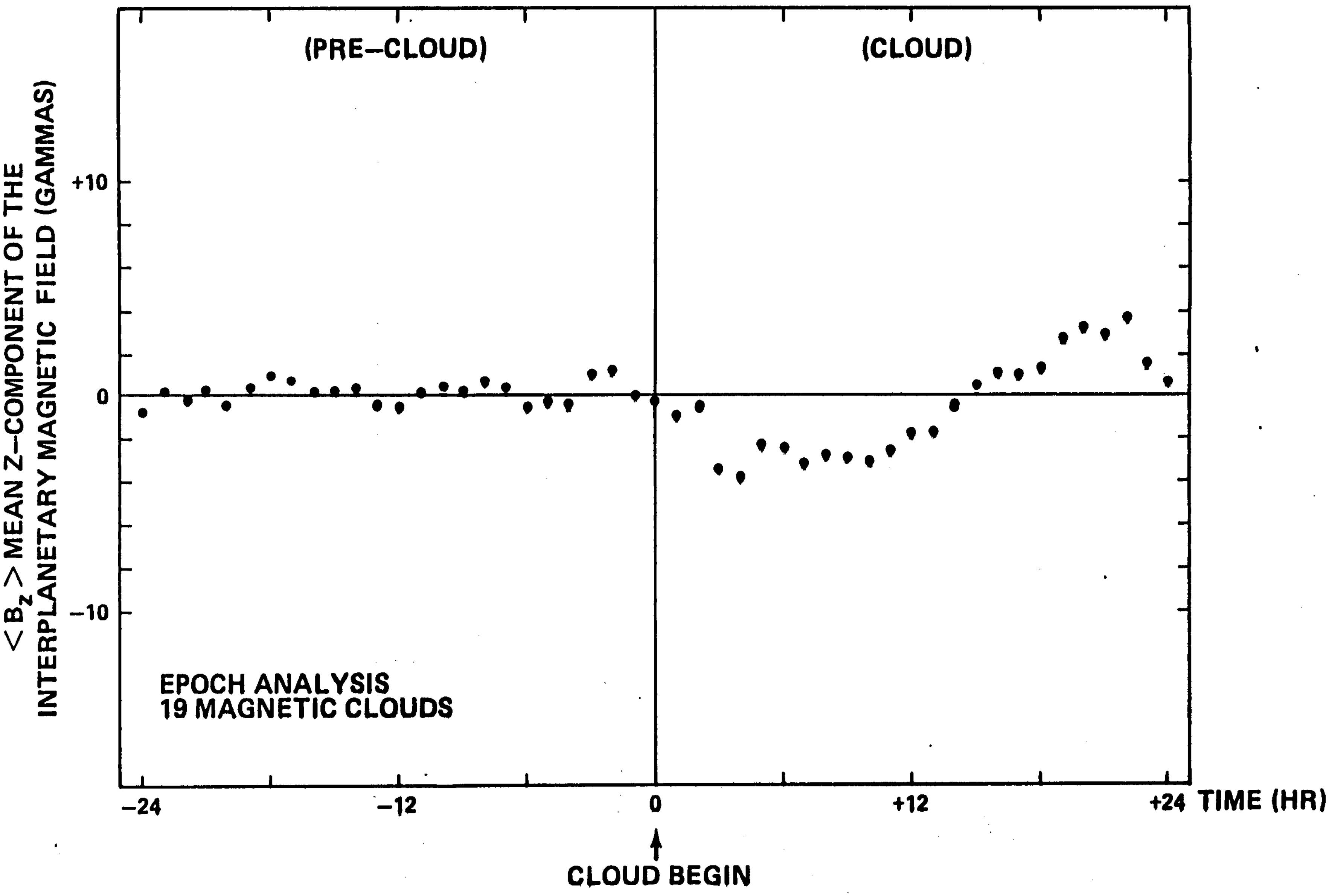
Figure Captions

FIGURE	CAPTION
1a	Superposed epoch analysis of the <Dst> geomagnetic index for 19 magnetic clouds, covering the interval 24 hr either side of cloud onset at Earth. Mean value ($\bar{x}$), standard deviation (s), and number (n) of data points are identified for the pre-cloud portion.
1b	Superposed epoch analysis of the <Dst> geomagnetic index for 19 control (no cloud) periods, covering the interval 24 hr either side of control onset. Mean value ($\bar{x}$), standard deviation (s), and number (n) of data points are identified.
2	Superposed epoch analysis of <Bz>, the mean Z-component of the interplanetary magnetic field (IMF), for 19 magnetic clouds.
3a	Superposed epoch analysis of <Dst>, the mean geomagnetic index, for 10 clouds with geomagnetic storms (denoted ●) and 9 clouds without geomagnetic storms (denoted ○).
3b	Superposed epoch analysis of <Bz>, the mean Z-component of the IMF, for 10 clouds with geomagnetic storms (denoted ●) and 9 clouds without geomagnetic storms (denoted ○).


(a)
(PRE–CLOUD)
(CLOUD)
X̄ = –7.42
S = 20.72
n = 456
EPOCH ANALYSIS
19 MAGNETIC CLOUDS
< Dst > MEAN GEOMAGNETIC INDEX (GAMMAS)
0
–10
–20
–30
–40
–24
–12
0
+12
+24
TIME (HR)
CLOUD BEGIN
(b)
X̄ = –9.08
S = 17.71
n = 931
EPOCH ANALYSIS
19 CONTROL PERIODS
< Dst > MEAN GEOMAGNETIC INDEX (GAMMAS)
0
–10
–20
–30
–24
–12
0
+12
+24
TIME (HR)
CONTROL BEGIN



(PRE–CLOUD)
(CLOUD)
$\langle B_z \rangle$ MEAN Z–COMPONENT OF THE INTERPLANETARY MAGNETIC FIELD (GAMMAS)
+10
0
–10
EPOCH ANALYSIS
19 MAGNETIC CLOUDS
–24
–12
0
+12
+24
TIME (HR)
CLOUD BEGIN

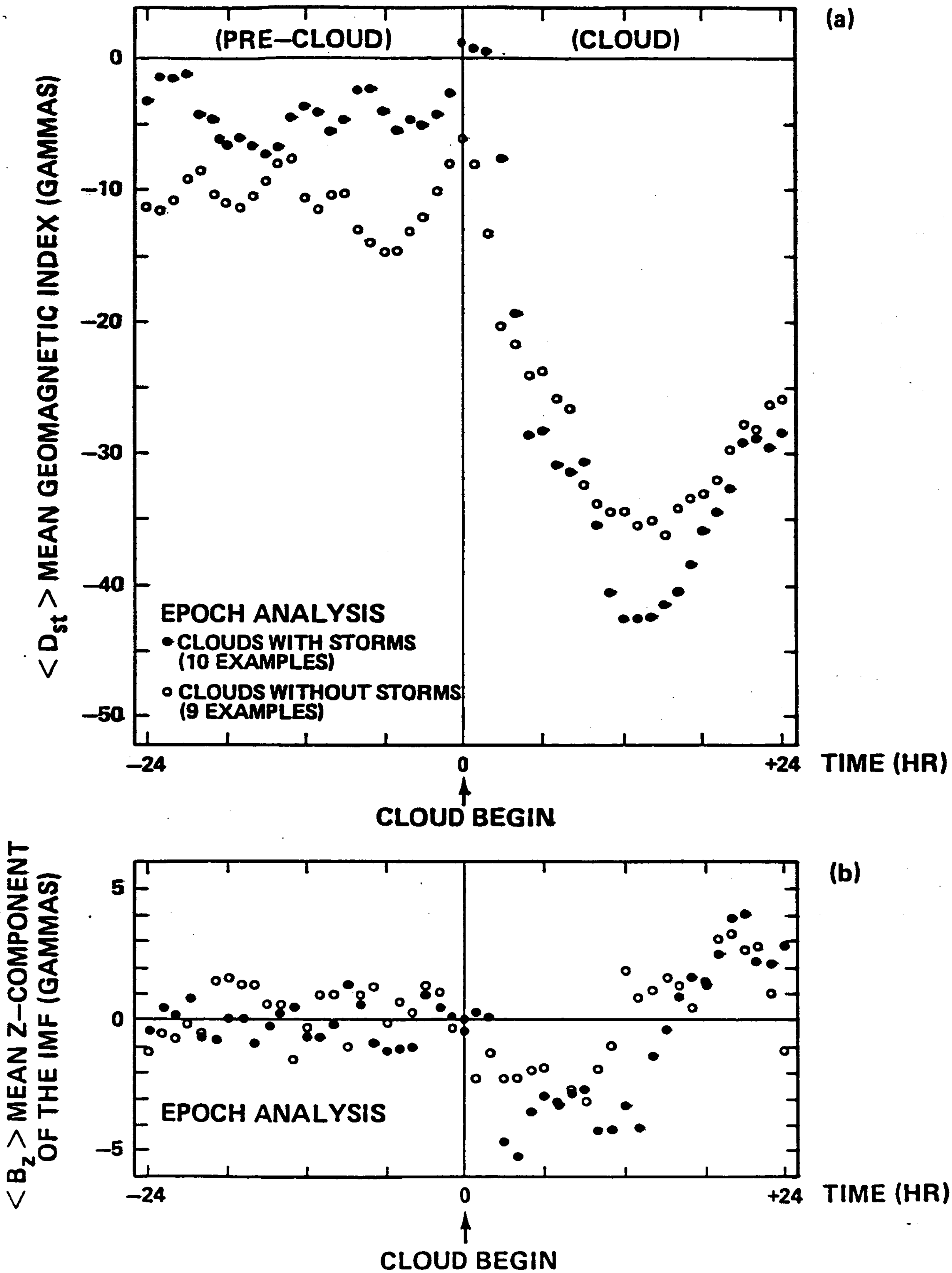

(a)
(PRE–CLOUD)
(CLOUD)
< D_st > MEAN GEOMAGNETIC INDEX (GAMMAS)
0
–10
–20
–30
–40
–50
EPOCH ANALYSIS
• CLOUDS WITH STORMS (10 EXAMPLES)
○ CLOUDS WITHOUT STORMS (9 EXAMPLES)
–24
0
+24
TIME (HR)
CLOUD BEGIN
(b)
< B_z > MEAN Z–COMPONENT OF THE IMF (GAMMAS)
5
0
–5
EPOCH ANALYSIS
–24
0
+24
TIME (HR)
CLOUD BEGIN

Table Captions

TABLE	CAPTION
1	Contingency table of observed distribution for magnetic clouds and geomagnetic storms.
2	Contingency table of observed distribution for magnetic clouds and types of geomagnetic storms.

CONTINGENCY TABLE OF OBSERVED DISTRIBUTION

MAGNETIC CLOUD (GROUP)		COMMENCEMENT OF PRINCIPAL MAGNETIC STORM WITHIN 1 HR OF CLOUD COMMENCEMENT? YES	NO	
A	E	2	2	$P \approx 0.21$
	C	0	4	
B	E	3	4	$P \approx 0.10$
	C	0	7	
C	E	5	3	$P \approx 0.01$
	C	0	8	
B & C	E	8	7	$P < 0.01$
	C	0	15	
ALL	E	10	9	$P < 0.01$
	C	0	19	

GROUP A = CLOUDS FOLLOWING SHOCKS
B = CLOUDS PRECEDING INTERACTION REGIONS
C = CLOUDS WITH COLD MAGNETIC ENHANCEMENTS

E = EVENT
C = CONTROL
P = PROBABILITY (PERCENT)

CONTINGENCY TABLE OF OBSERVED DISTRIBUTION

MAGNETIC CLOUD (GROUP)		GRADUAL COMMENCEMENT YES	GRADUAL COMMENCEMENT NO		SUDDEN COMMENCEMENT YES	SUDDEN COMMENCEMENT NO	
A	E	0	4	$P = 1.00$	2	2	$P \approx 0.21$
	C	0	4		0	4	
B	E	3	4	$P \approx 0.10$	0	7	$P = 1.00$
	C	0	7		0	7	
C	E	5	3	$P \approx 0.01$	0	8	$P = 1.00$
	C	0	8		0	8	
B & C	E	8	7	$P < 0.01$	0	15	$P = 1.00$
	C	0	15		0	15	
ALL	E	8	11	$P < 0.01$	2	17	$P \approx 0.24$
	C	0	19		0	19	

GROUP A = CLOUDS FOLLOWING SHOCKS
B = CLOUDS PRECEDING INTERACTION REGIONS
C = CLOUDS WITH COLD MAGNETIC ENHANCEMENTS

E = EVENT
C = CONTROL
P = PROBABILITY (PERCENT)